Quantitative assessment of tip saturation for high quality piezocone testing

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ABSTRACT

The research compares 2 CPTU profiles obtained with a same piezocone setup but having a different degree of saturation associated with the pore pressure measuring system. In the reference test, saturation was performed injecting 20cS silicon oil in the conduit connecting the porous stone to the pressure sensor and applying vacuum while submerged in oil for 15 minutes. The piezocone tip was then assembled with a saturated porous stone while submerged in oil. In the other test, the degree of saturation was purposely lowered by introducing air in the same conduct, whereas all other saturation steps were unchanged. The degree of saturation was compared quantitatively by measuring an analogue of the Skempton's coefficient B, which is routinely used in laboratory testing to assess specimen saturation in a triaxial cell. The value associated with the saturation condition was measured employing a tool specifically designed for this purpose. The saturation procedures adopted were selected based on preliminary experimental activity in the laboratory, which provided target values of the pore pressure parameter corresponding to full or partial saturation. The CPTUs were performed at a test site presenting 10m clay unit followed by sand. The profiles measured were compared in terms of pore-pressure profiles, as well as the influence this had on corrected tip resistance, Soil Behaviour Type classification and mechanical properties. Additionally, a dissipation was performed for each test to compare consolidation parameters.

Keywords: saturation; pore water pressure; data quality.

1. Introduction

In many projects, Cone Penetration Testing with pore-pressure measurements (CPTU) is the main source of information with regards to stratigraphy, mechanical and hydraulic properties. Besides inherent variability, uncertainty in measurements may result from the piezocone. Equipment malfunctioning can be considered rare, though this risk could increase if maintenance or adequate calibration of sensors are not routinely carried out. A way more common uncertainty in piezocone measurements is however due to incomplete saturation or loss of saturation of the pore-pressure system. The effects on the pore-pressure response have been reported long ago (Lunne et al. 1997), but thereafter little systematic research has been performed (DeJong et al. 2007, DeBacker et al. 2022) and the issue remains a major source of uncertainty in engineering practice.

Rocchi et al. (2017) developed a tool to assess quantitatively the degree of saturation of piezocones a priori (i.e. before CPTU is performed and the pore-pressure response is observed). The tool allows applying a known pressure impulse to the piezocone and measures its response. The incremental ratio between the measured and applied pressure is correlated to the saturation degree of the piezocone (Rocchi et al. 2023), according to the same practice that is conventionally adopted in geotechnical laboratories when performing triaxial tests.

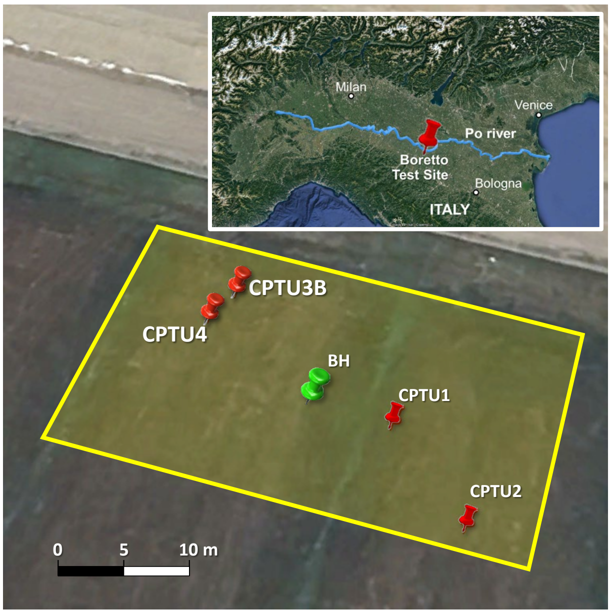

Figure 1. Site and tests location.

The work presented here compares the pore-pressure response of two piezocone tests performed at different initial degrees of saturation as measured by the tool mentioned. The tests were carried out at the end of November 2023 at a pilot test site located in Boretto (Reggio Emilia province, Italy), as part of a site investigation campaign devised within the European project LIFE SandBoil (https://lifesandboil.eu) for the design of a full-scale model of backward erosion piping phenomena below river embankments.

2. Stratigraphy

The Boretto test site is located in the Po river plain, at about 2 km away from the watercourse. The shallowest soil deposits encountered in this area result from sediment accumulation in a continental depositional environment, due to the Po river. They mainly consist of a 15 m thick layer of clays, clayey silts and silty clays, referable to floodplain deposits, followed by a rather thick, fine to medium coarse-grained soil unit, typically referred to as "Padano Aquifer". In this layer, sub-artesian conditions occur, while a shallow unconfined aquifer exists within the fine-grained soil unit. According to groundwater monitoring campaigns carried out in last years, the piezometric surface level in the Padano Aquifer, governed by the water level in the adjacent river, is approximately 1–2 m lower than the phreatic surface, but during flood events the water head condition is reversed (Merli, 2015). The tests performed in Boretto, including continuous coring boreholes and CPTU, confirmed the expected soil stratigraphy. The tests were generally pushed to 20m depth and stopped when penetration of the sandy aquifer was clearly achieved. The water table detected in the unconfined aquifer during the testing campaign turned out to be 3 m below the ground surface in the borehole.

3. Methodology

Four piezocone tests (CPTU1-CPTU4) were performed using a 10cm^2 piezocone with area ratio a=0.58. A few dissipations tests were also performed in each test (11 in total).

The piezocone was saturated by applying vacuum for 10 minutes while submerged under silicon oil before mounting on the piezocone presaturated bronze filters and tightening the tip. The assembled piezocone was then placed under vacuum an additional 10 minutes. Small filter papers were added between the filter and the metal parts of the piezocone tip. Note that this is not the same piezocone as used in Rocchi et al. (2023) and therefore, the saturation checking tool appears to have the potential to be applied to a range of piezocones.

After completing saturation, the device was slid on the piezocone, which at this time was not covered with a rubber membrane, and an initial nominal increment of 50kPa was applied, followed by 2 additional increments.

The pore water pressure parameter $B*$, referable to the saturation degree of the piezocone tip, was then calculated as:

$$B^* = \Delta u_2 / \Delta p \quad (1)$$

where Δp is the applied pressure increment and Δu_2 is the measured pore water pressure increment.

The $B*$ value was not measured for CPTU1. In CPTU2, the initial piezocone response was practically the same as the pressure impulse applied, resulting in $B*$ = 0.98, which was confirmed in the following steps. In CPTU4 the initial piezocone response was almost the same as the pressure impulse applied, resulting in $B*$ = 0.94. In subsequent steps, the applied and measured pressures were identical, thus leading to B=1. CPTU4 was therefore selected as the control test.

The effect of reduced degree of saturation was assessed in CPTU3B, where the piezocone was prepared using the same exact procedure. However, the filter was then lightly dabbed with a paper tissue. Based on a nominal initial applied increment of 50kPa, the measured increment resulted in $B*$ = 0.92, which dropped to $B*$ = 0.84 for the following increments. It should be observed that this operation does not provide a well-controlled degree of saturation, compared to the procedure applied in laboratory by Rocchi et al. (2023), where filters degree of saturation was assessed by weight reduction. The weight loss required to meaningfully use the latter procedure, however led to values of B* that appear to be unrealistically low compared to what can be expected in the field. Also compared to the laboratory, the piezocone in the field was not desaturated by injecting a controlled amount of air in the pore-pressure cavity before starting the saturation procedure.

Note that in order to avoid desaturation during penetration of the shallowest soil layer above water table, a pre-drilling of 3 meters was carried out for tests CPTU2 and CPTU4, so that penetration could occur only in fully saturated conditions. In CPTU3B penetration started at the ground level.

4. Results

The CPTU profiles obtained for CPTU3B and CPTU4, together with the soil type behaviour, are presented in Fig.2, where q_t is the corrected tip resistance, f_s the sleeve friction and u is the pore water pressure measured in position 2, i.e. just behind the cone. Values of the equilibrium pore water pressure, as recorded at the end of a few dissipation tests from CPTU4, are also superimposed on the u_2 profile.

The results are remarkably reproducible in terms of tip resistance and sleeve friction, while the response in pore water pressure is clearly different. The pore water pressure response within the clayey layers in CPTU3B is extremely low and can almost certainly be only attributed to low saturation despite the relatively high value of $B*$ measured at the start of the test.

The recorded u_2 values were evaluated taking into account that the pore water pressure profile at equilibrium is governed by two different piezometric levels. The phreatic surface in the clay layer was assumed to be at approximately 3m depth from the ground surface, as detected in a borehole located nearby. The piezometric level in the Padano Aquifer was instead deduced from the u_2 profile of CPTU4 and turned out to be close or slightly higher than the phreatic surface, likely due to heavy rain just before the testing campaign.

The soil type behaviour I_{cn} (also presented in Fig.2) was calculated iteratively based on the normalized tip resistance $Q_{tn} = [(q_t - \sigma_{v0})/\sigma'_{v0}] \cdot (p_a/\sigma'_{v0})^n$ and the friction ratio $F_R = 100 \cdot f_s/(q_t - \sigma_{v0})$, according to Robertson (2009).

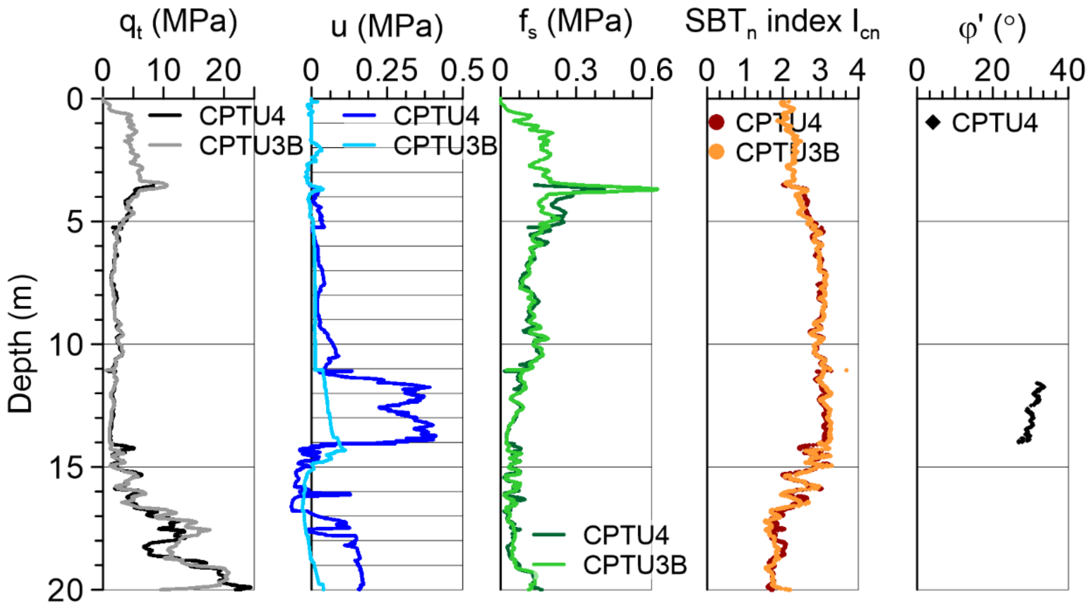

Figure 2. Comparison of CPTU profiles for fully saturated conditions (CPTU4) and partially saturated conditions (CPTU3B).

Because of the extremely poor performance in terms of pore water pressure for CPTU3B, the correction on the cone resistance calculated on the basis of pore water pressures, i.e. $u(1-a)$, is significantly different. Specifically in the clay layer between 11.5 and 14m depth the correction is almost three times for CPTU4 (173kPa) compared to CPTU3B (47kPa). However, within the stratigraphic conditions tested this did not hinder the correct identification of the soil stratigraphy when based on the sleeve friction ratio since the soil type behaviour index I_{cn} is practically the same for the two tests.

When considering the normalized pore water pressure $B_q = (u - u_0)/(q_t - \sigma_{v0})$ for stratigraphic recognition, the layer between 11.5 and 14m is identified as silty clay in CPTU3B, while it ranges from silty clay to clay for CPTU4 (Fig.3a). Based on a detailed analyses of the tip resistance, pore water pressure and dissipations, including the modified classification chart of Schneider et al. (2008) (Fig.3b), this layer varies from transitional soils to silts and clays of low rigidity index. Analysis on this chart also explains the relatively high tip resistance when compared to the normal to lightly overconsolidated state; as well as the unconventionally low pore water pressure generated between 3 and 11m depth, which is also classified as transitional on this chart. Even the layers identified as drained sand according to Schneider et al. (2008) chart are relatively rich in fines when analysed from the borehole logs.

The application of the well-known formula by Senneset et al. (1988) to CPTU4 data for the estimate of the effective shear strength resulted in φ'=30.2°, with standard deviation σ=2.4°. Drained parameters could not be estimated based on CPTU3B because the required conditions on B_q (i.e. $0.1 < B_q < 1$) were not satisfied due to the unreliable pore water pressure measurements.

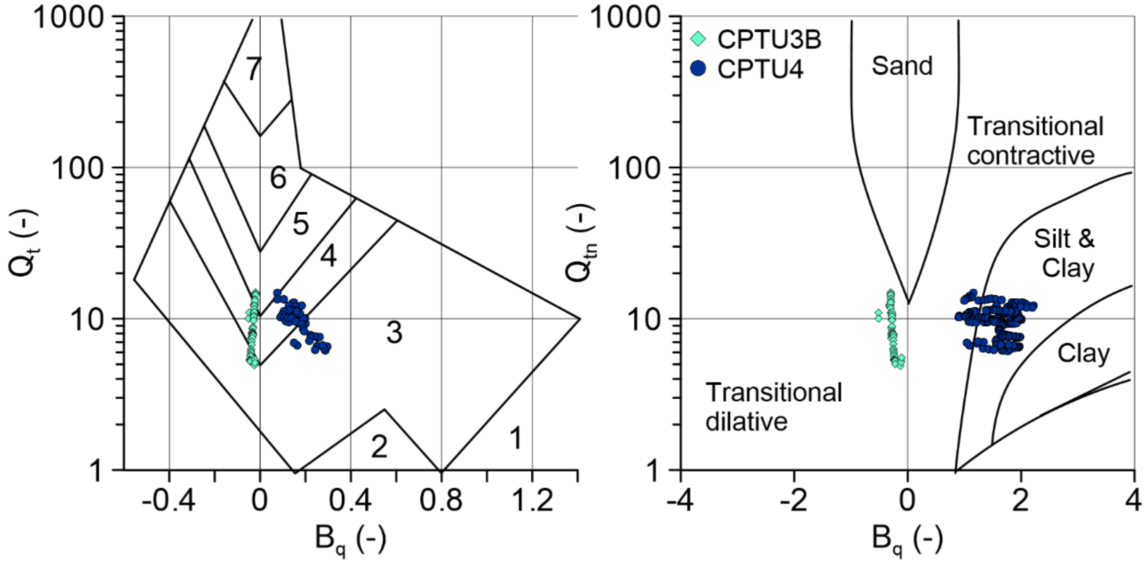

Figure 3. Soil classification for CPTU4 based on (a) Robertson (1990) and (b) Schneider et al. (2008).

With respect to the undrained parameters, the undrained shear strength was calculated as $s_u = (q_t - \sigma_{v0})/N_k$, where $N_k = 10$ was employed for both tests and it was considered a suitable assumption based on light overconsolidation (average OCR = 2 for CPTU4). The average value obtained for CPTU4 was 148kPa with standard deviation $\sigma = 33$kPa, while for CPTU3B, $s_u = 134$kPa $\sigma = 40$kPa, which corresponds to about 10% less.

Furthermore, out of the dissipation tests performed, Fig.4 shows results of tests carried out at 5.0m depth, thus in clay/silty clay. From interpretation of the curves, the coefficient of horizontal consolidation turns out to be overestimated by a factor 2 for the test with low saturation, given that $c_h = 6.5 \cdot 10^{-7}$m^2/s for CPTU4 and $c_h = 1.4 \cdot 10^{-6}$m^2/s for CTPu3B. Similarly for the hydraulic conductivity, where $k_h = 6.8 \cdot 10^{-10}$m/s and $k_h = 1.7 \cdot 10^{-9}$m/s for CPTU4 and CTPu3B, respectively. Note that estimates based on Q_t and I_{cn} obtained during penetration are 10^{-9}m/s and 10^{-8}m/s and do not depend on the degree of saturation but are essentially an order of magnitude higher.

5. Conclusions

The work presented compares two piezocone tests performed with optimal and suboptimal saturation of the pore water pressure system. The saturation conditions were measured using a tool built for the purpose, which provides a $B*$ value analogous to the pore-pressure Skempton parameter (1954) that is measured in a triaxial test before testing for similar purposes.

Despite the relatively small difference in the saturation conditions, the values measured were $B* = 1$ and $B* = 0.84$ for the two tests respectively, the pore water pressure response measured was dramatically different and almost non-existent in the test with lower saturation.

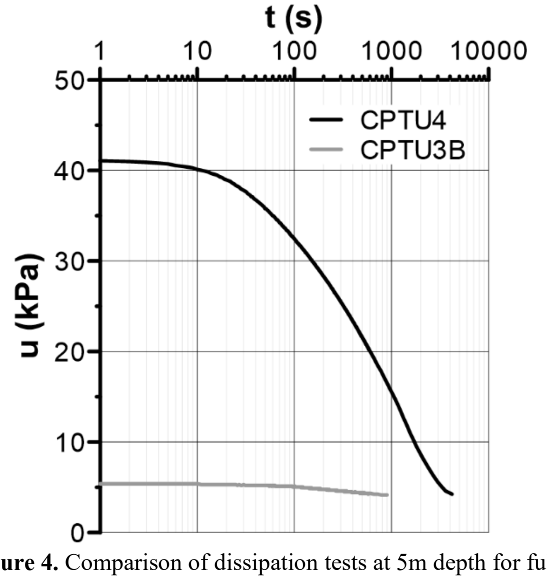

Figure 4. Comparison of dissipation tests at 5m depth for fully saturated conditions (CPTU4) and partially saturated conditions (CPTU3B).

A poor pore water pressure response is particularly detrimental in the case of complex stratigraphy as that presented here, because it is the only parameter that is not affected by scale, i.e. thin interbedding, when identifying boundaries between layers. Furthermore, it is an essential parameter to evaluate the phenomena of partial drainage.

With respect to the calculation of the corrected tip resistance, the low pore water pressure response may have a significant impact (up to 3 times in this case study) on the values of the corrected cone resistance, especially when very soft fine-grained soils, characterized by very low values of tip resistance, have to be considered. This could in turn severely affect the estimate of the undrained shear strength. Most importantly, low values in the measurement of u hinder entirely the possibility to calculate drained strength parameters for fine grained soil units.

With respect to hydraulic parameters, dissipation tests showed a discrepancy in the initial values ranging from 4 to 8 times lower for the test with low saturation. Whilst in this case the consolidation and hydraulic conductivity parameters were overestimated only by a factor 2, such issue would require further significant investigation, also in order to make the results of dissipation tests more trustworthy.

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